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Itoh et al.

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(54) **OPTICAL FIBER PROBE, OPTICAL DETECTION DEVICE, AND OPTICAL DETECTION METHOD**

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G02B 6/26 (2006.01)

(52) **U.S. Cl.** **250/227.28**; 385/31; 385/39

(58) **Field of Classification Search** 250/227.3, 250/227.11, 227.31, 227.32, 227.28, 216, 250/227.29; 352/12, 43, 123, 31, 33, 39; 73/105

See application file for complete search history.

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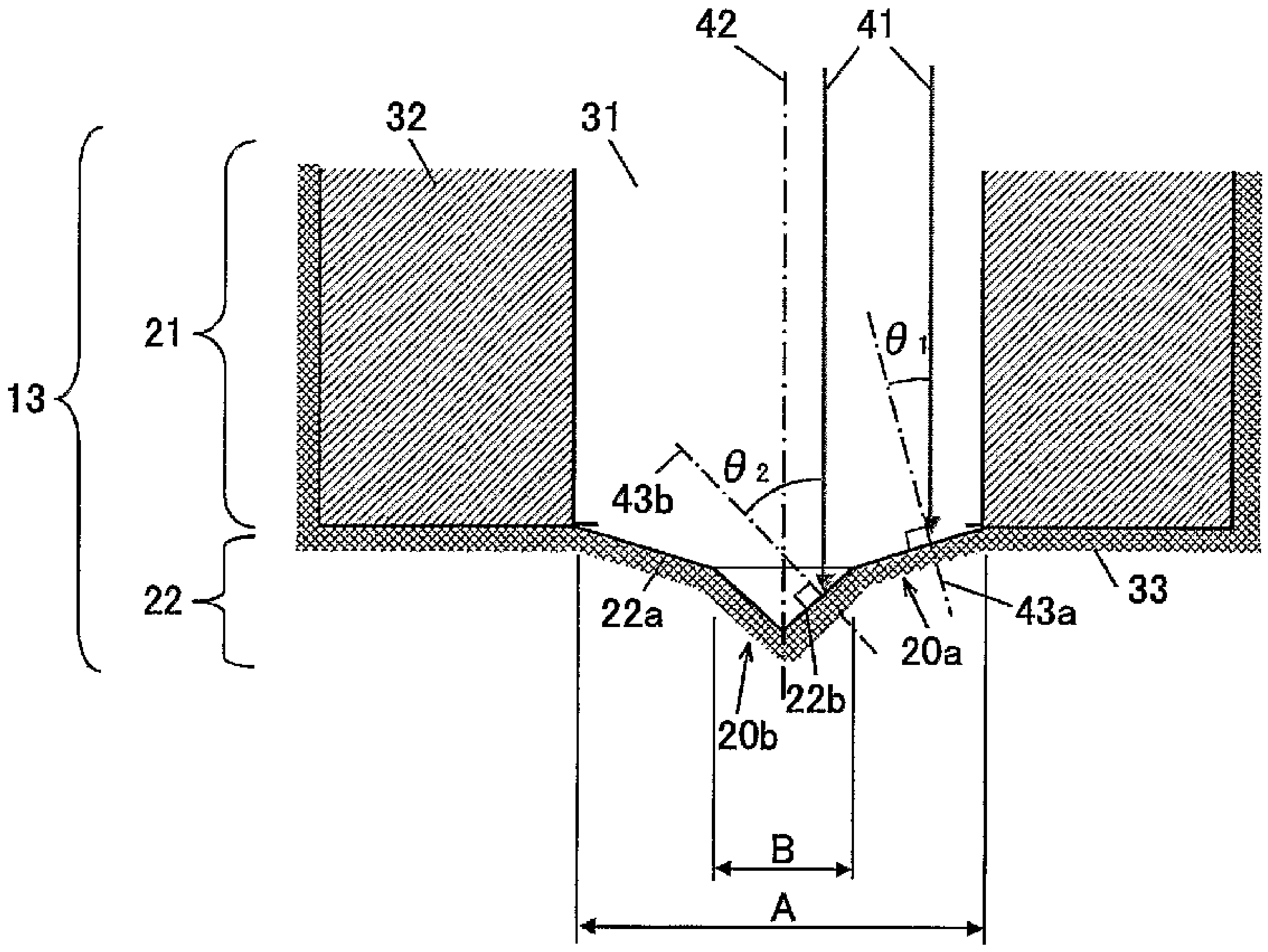
(74) *Attorney, Agent, or Firm*—Oblon, Spivak, McClelland, Maier & Neustadt, P.C.

(57) **ABSTRACT**

An optical detection device image is disclosed that allows fast measurements using near-field light at high resolution and high efficiency but without necessity of position alignment of an optical fiber probe. The optical detection device includes an optical fiber probe having a core for propagating light with an optical probe being formed at a front end of the core; a movement control unit to move the optical fiber probe to approach or depart from a sample; and a detection unit to detect light from the sample surface, wherein on the front end surface of the core of the optical probe, there are a first exit section on a peripheral side for emitting propagating light and a second exit section for seeping out the near-field light, the first exit section and the second exit section are formed in a concentric manner, and the tilt angle of the first exit section is different from the tilt angle of the second exit section.

23 Claims, 10 Drawing Sheets



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* cited by examiner

FIG.1

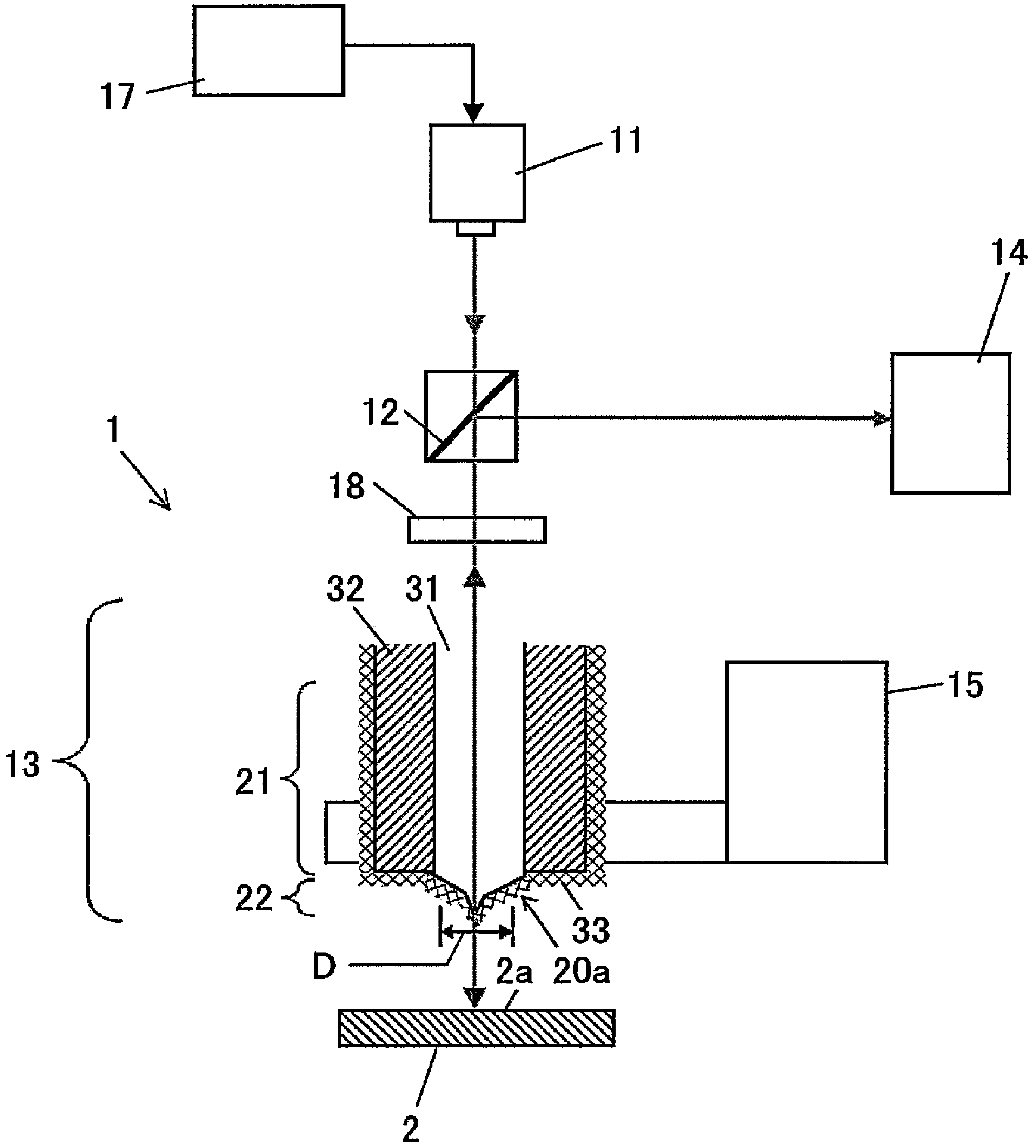


FIG.2

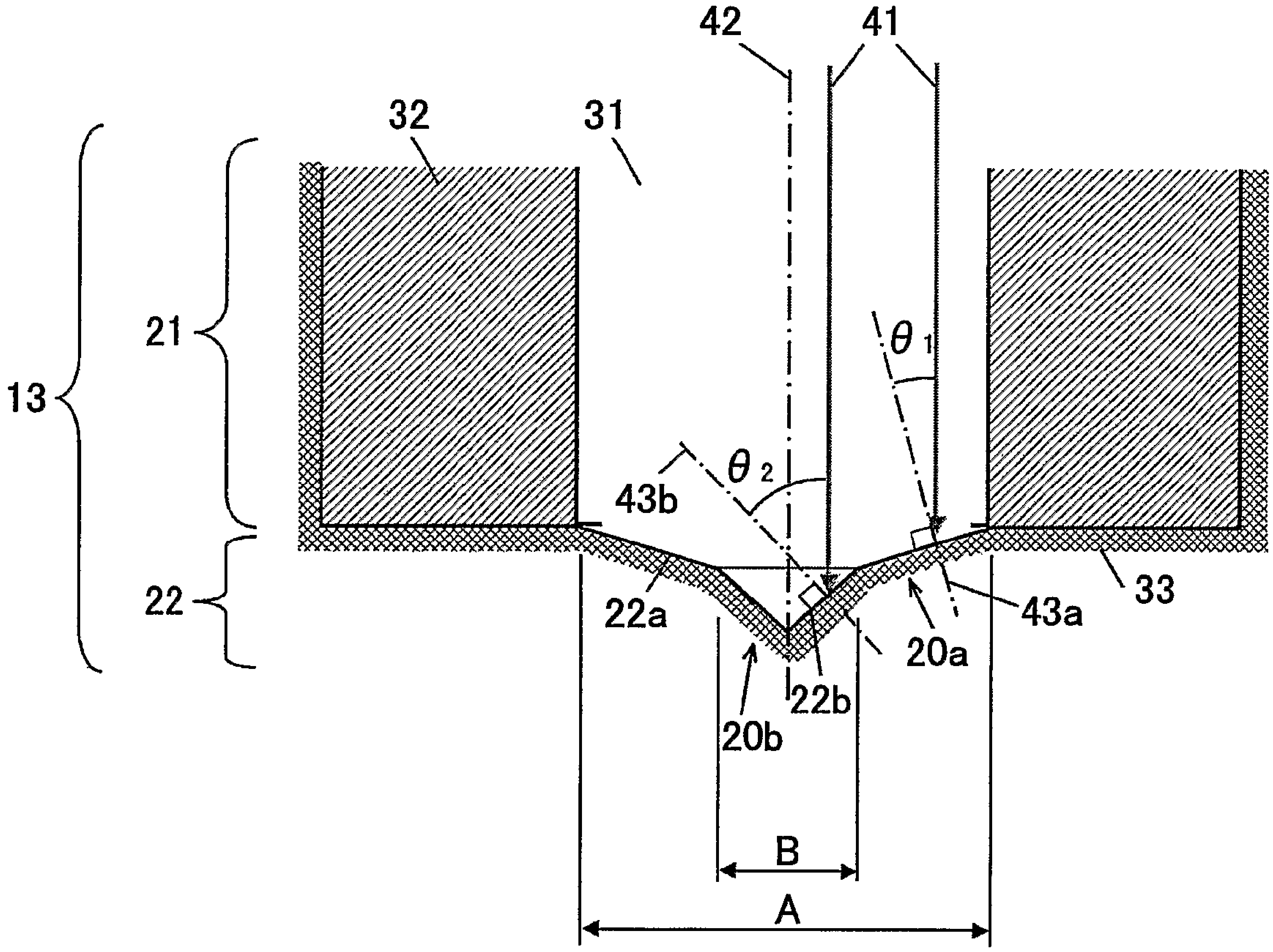


FIG.3

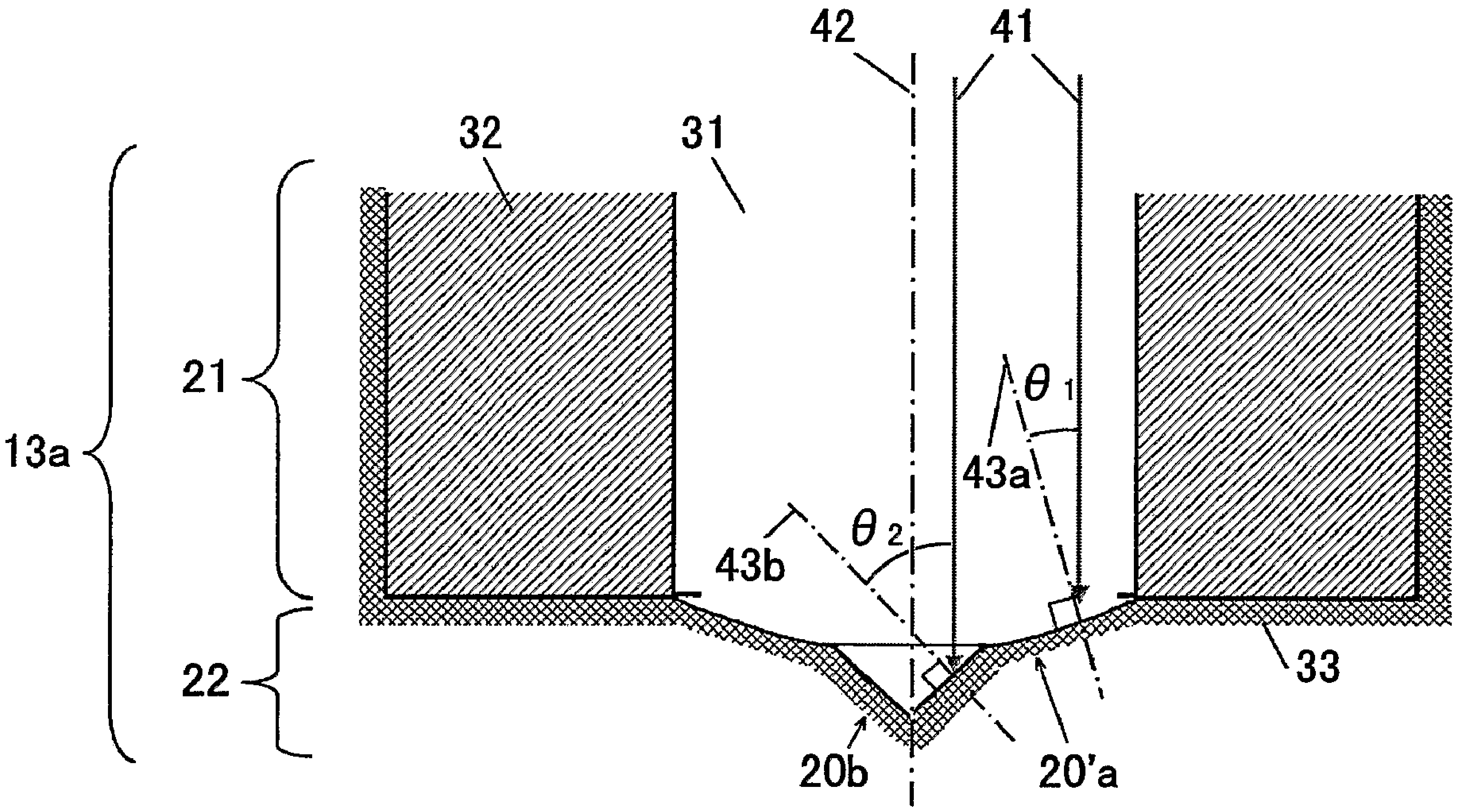


FIG.4

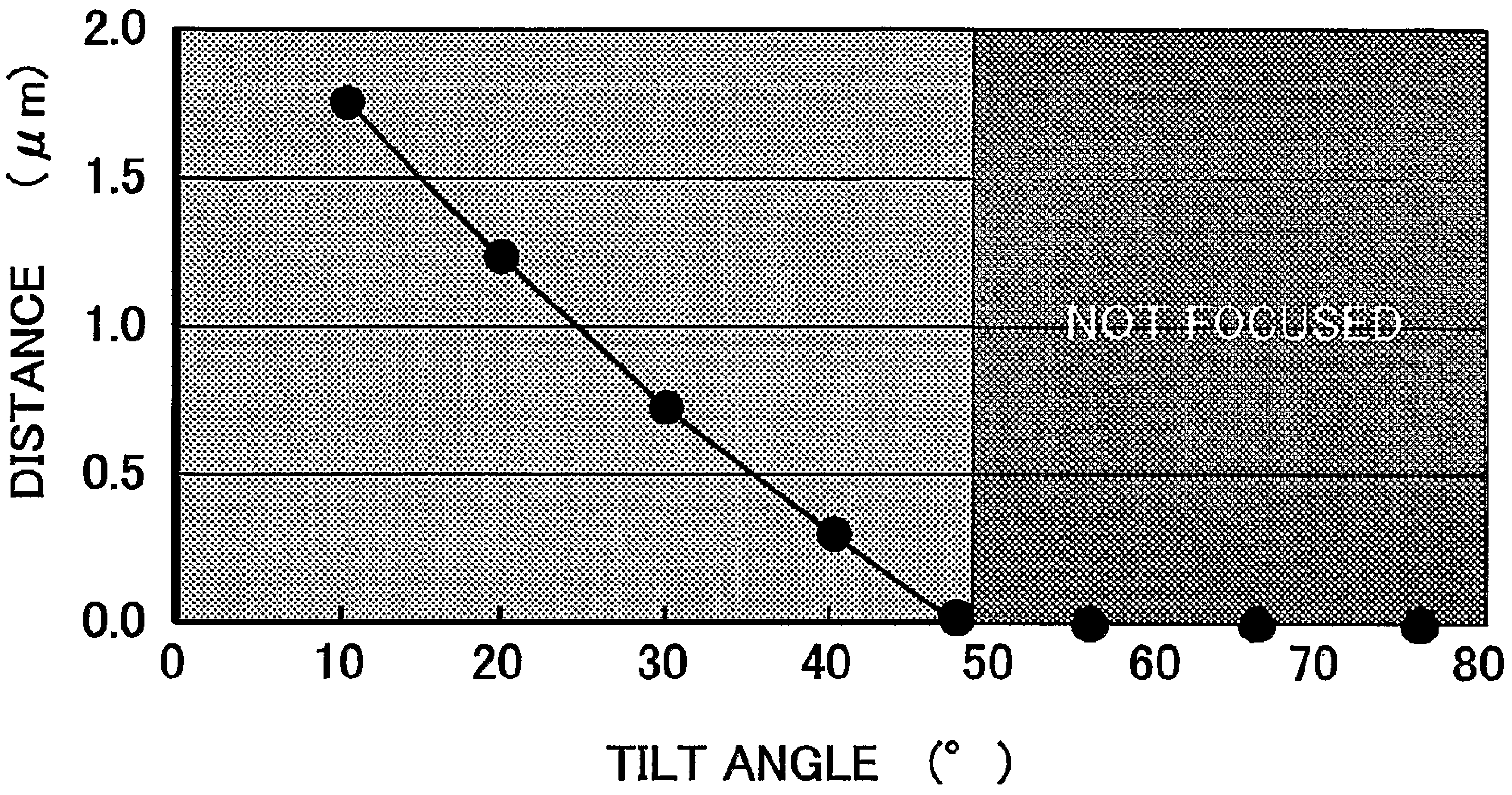

DISTANCE (μm)
2.0
1.5
1.0
0.5
0.0
0
10
20
30
40
50
60
70
80
TILT ANGLE (°)
NOT FOCUSED

FIG.5

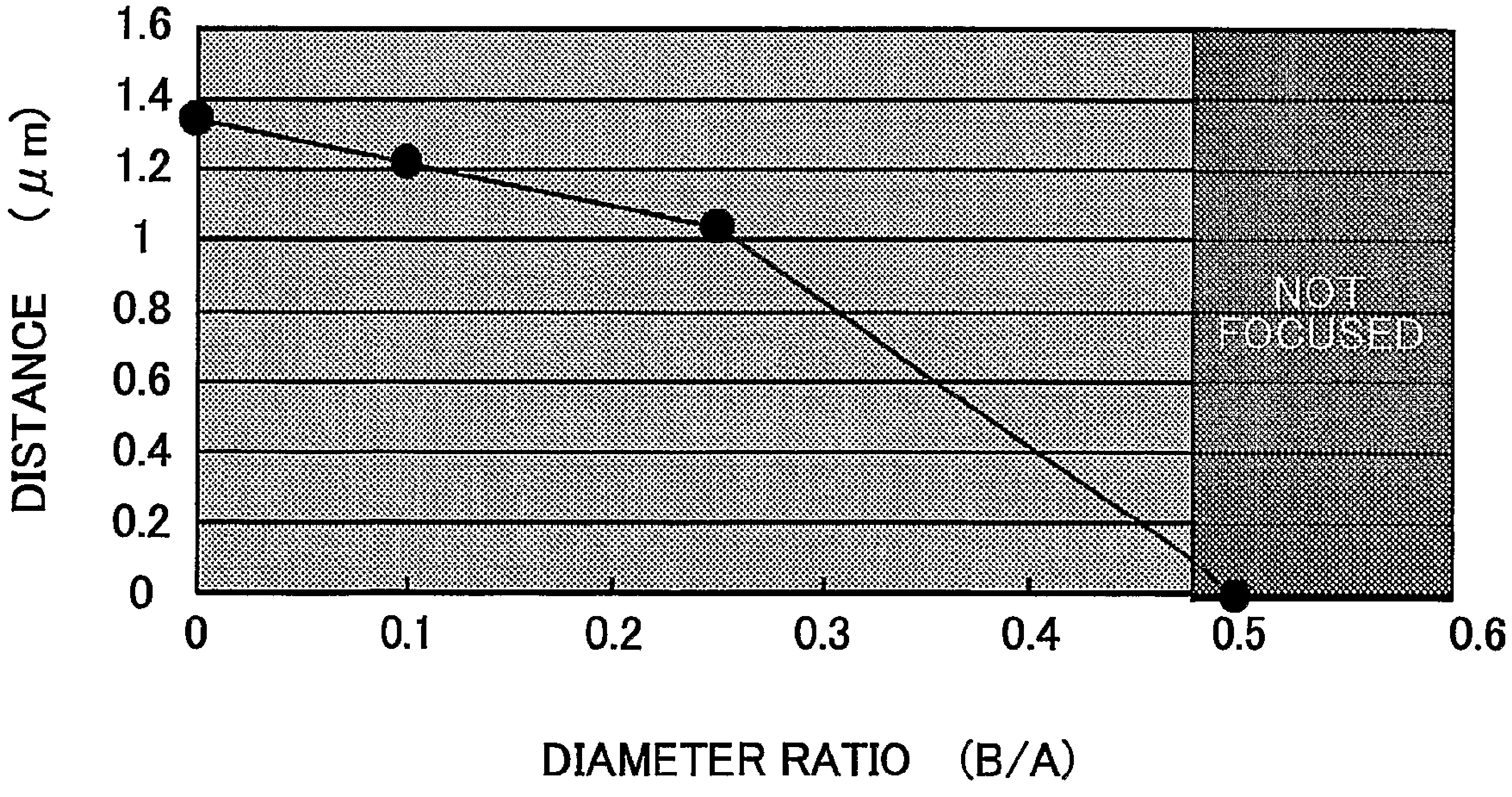

DISTANCE (μm)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
DIAMETER RATIO (B/A)
NOT FOCUSED

FIG.6

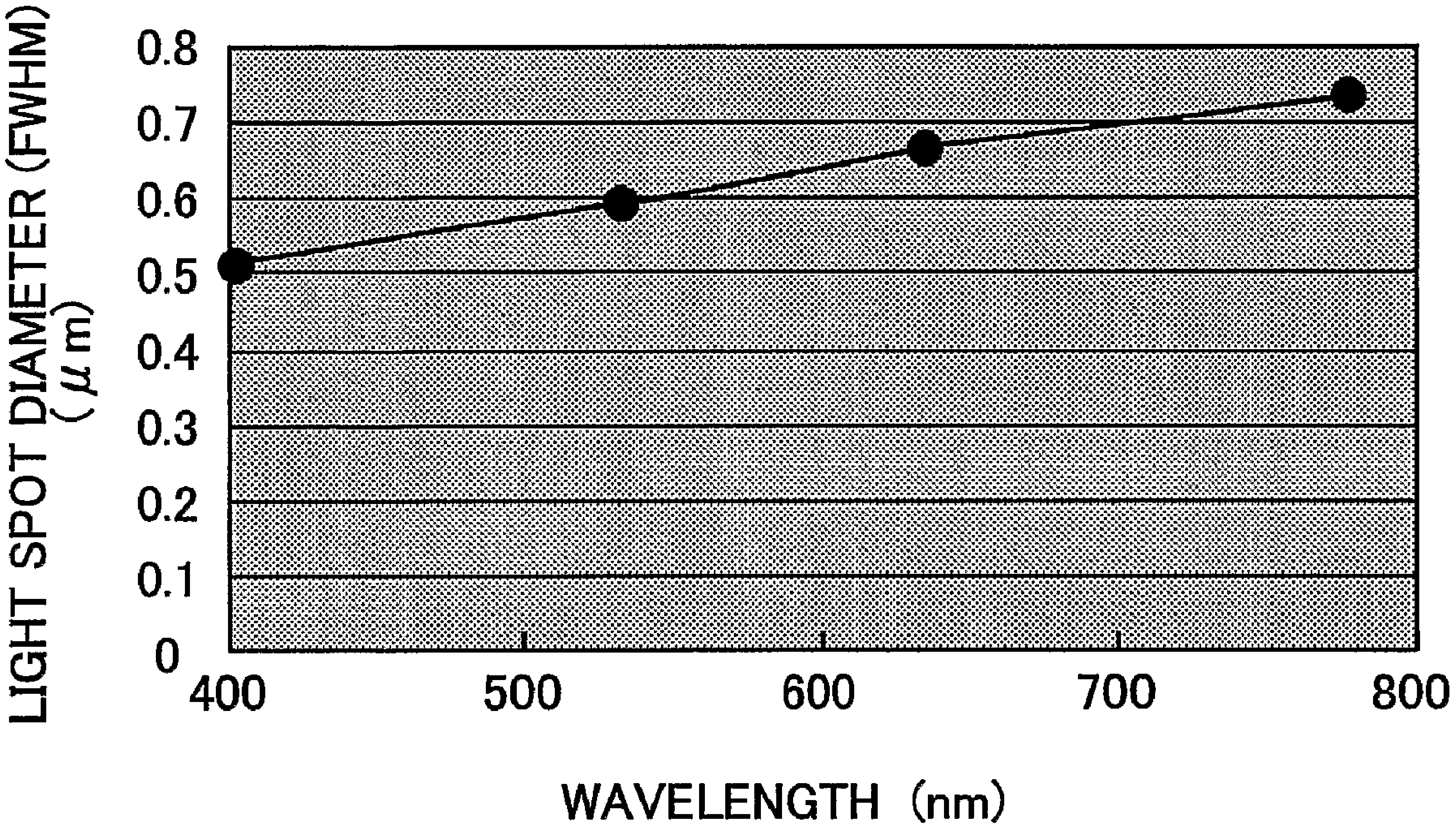

LIGHT SPOT DIAMETER (FWHM)
(μm)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
400
500
600
700
800
WAVELENGTH (nm)

FIG.7

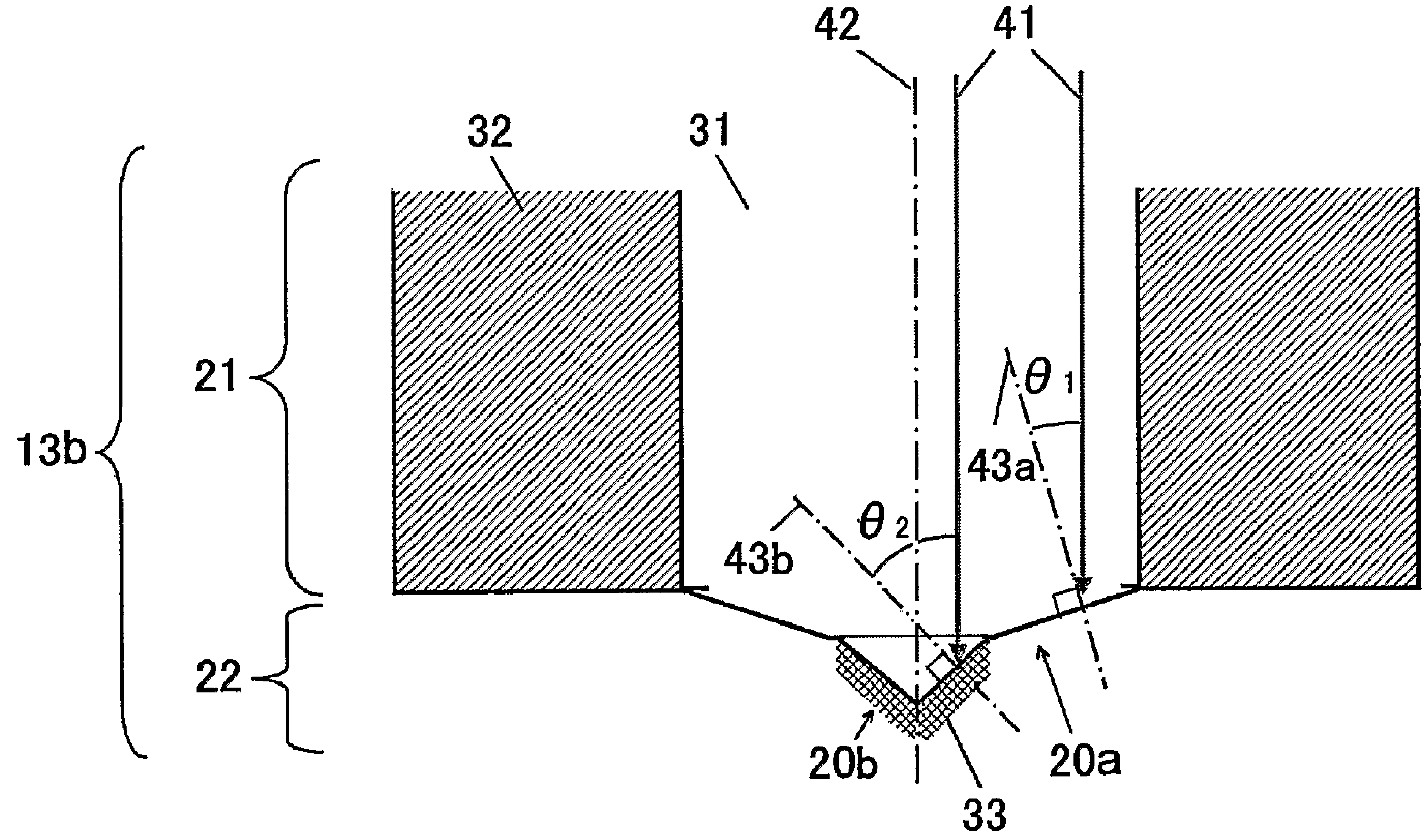


FIG.8

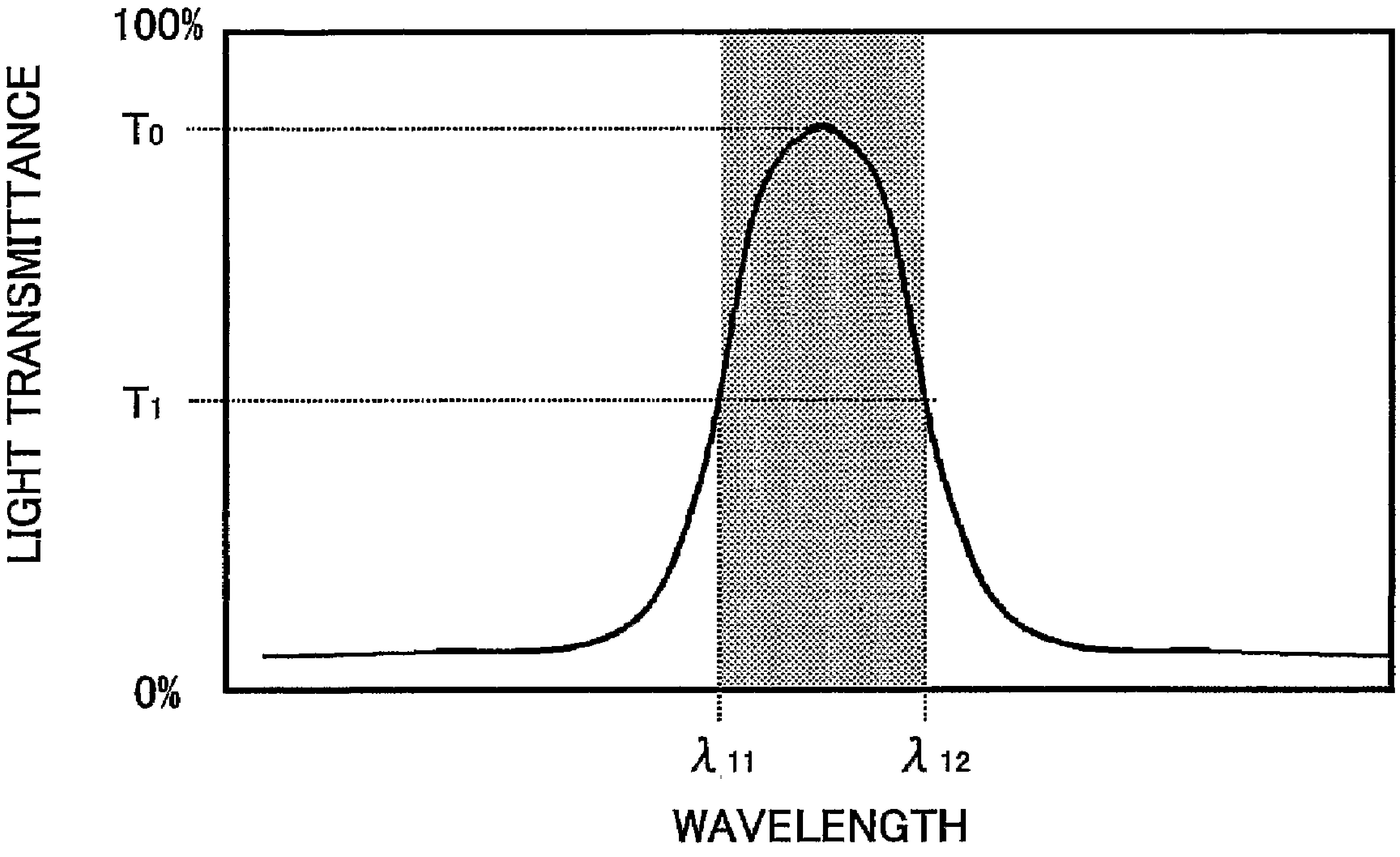


FIG.9

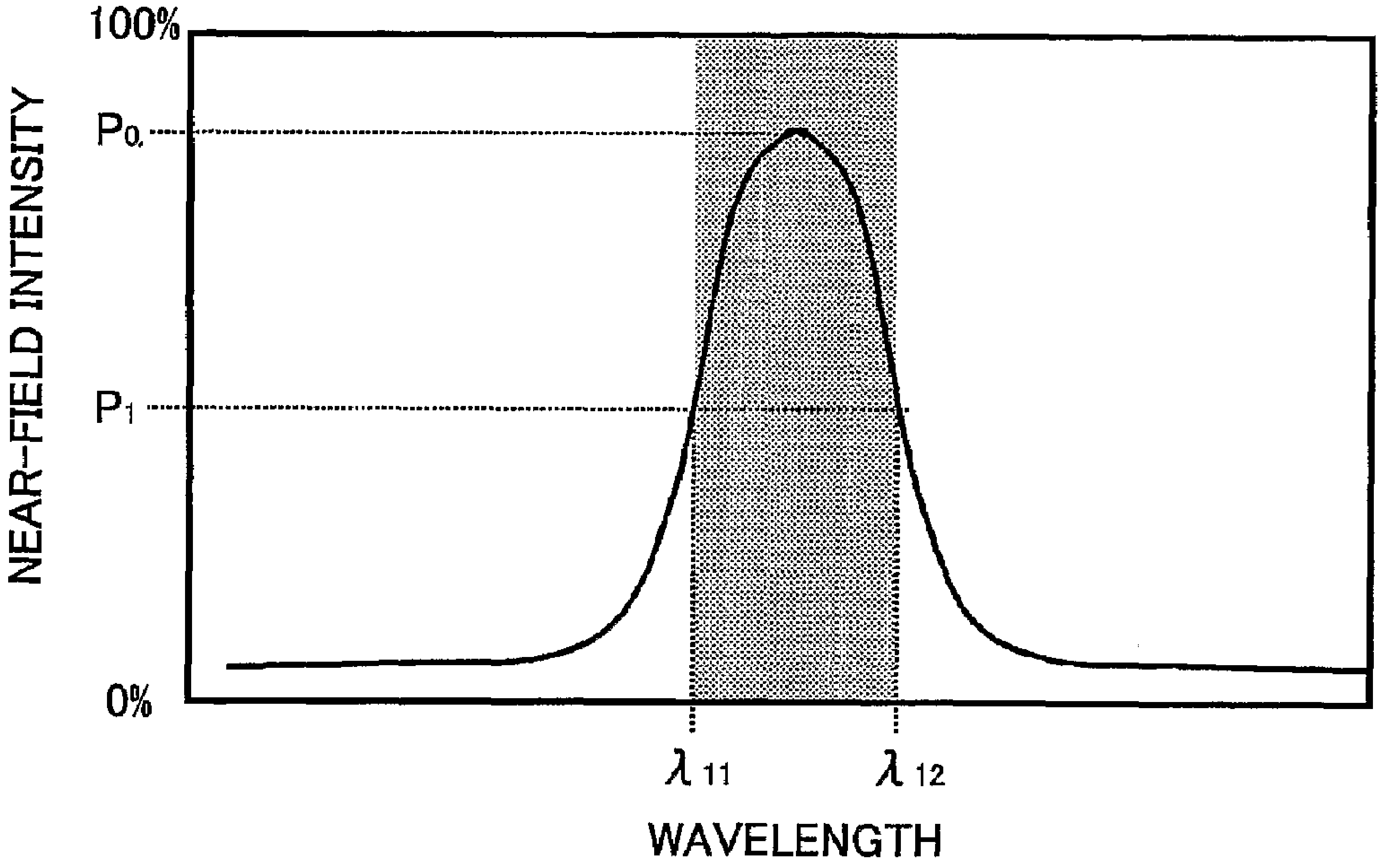

100%
P0
P1
0%
NEAR-FIELD INTENSITY
λ11
λ12
WAVELENGTH

FIG.10

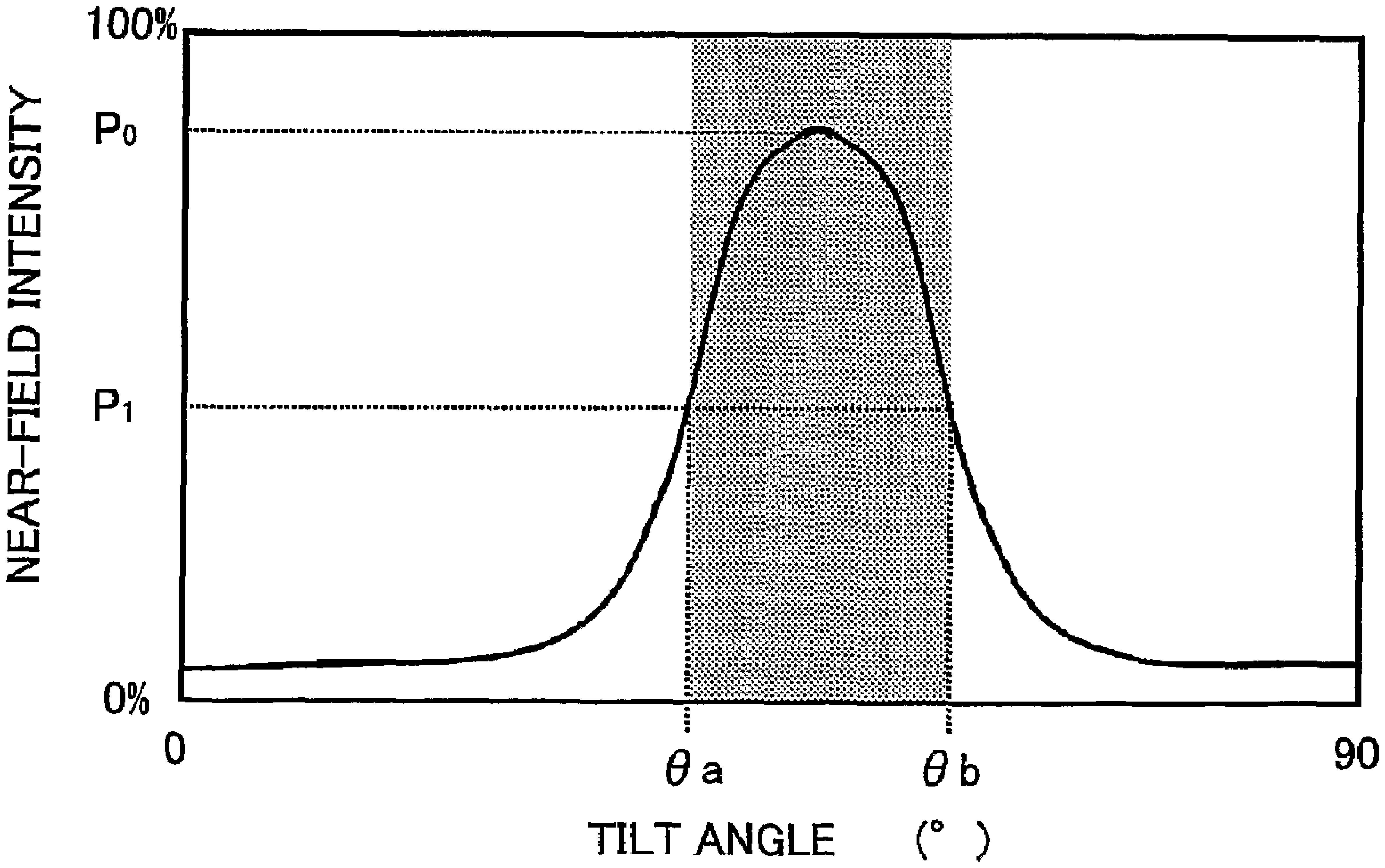

100%
P0
P1
0%
NEAR-FIELD INTENSITY
0
θa
θb
90
TILT ANGLE (°)

FIG.11

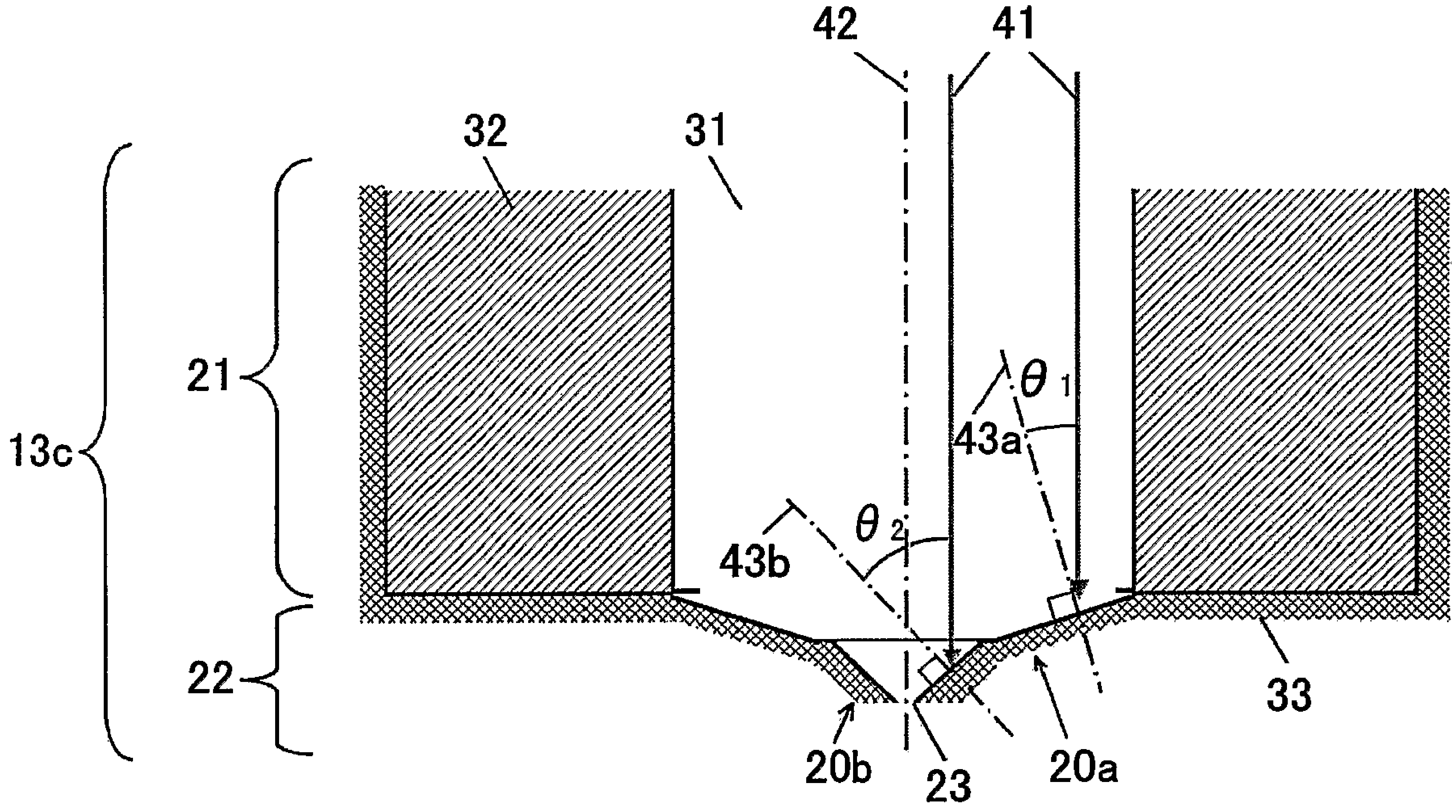
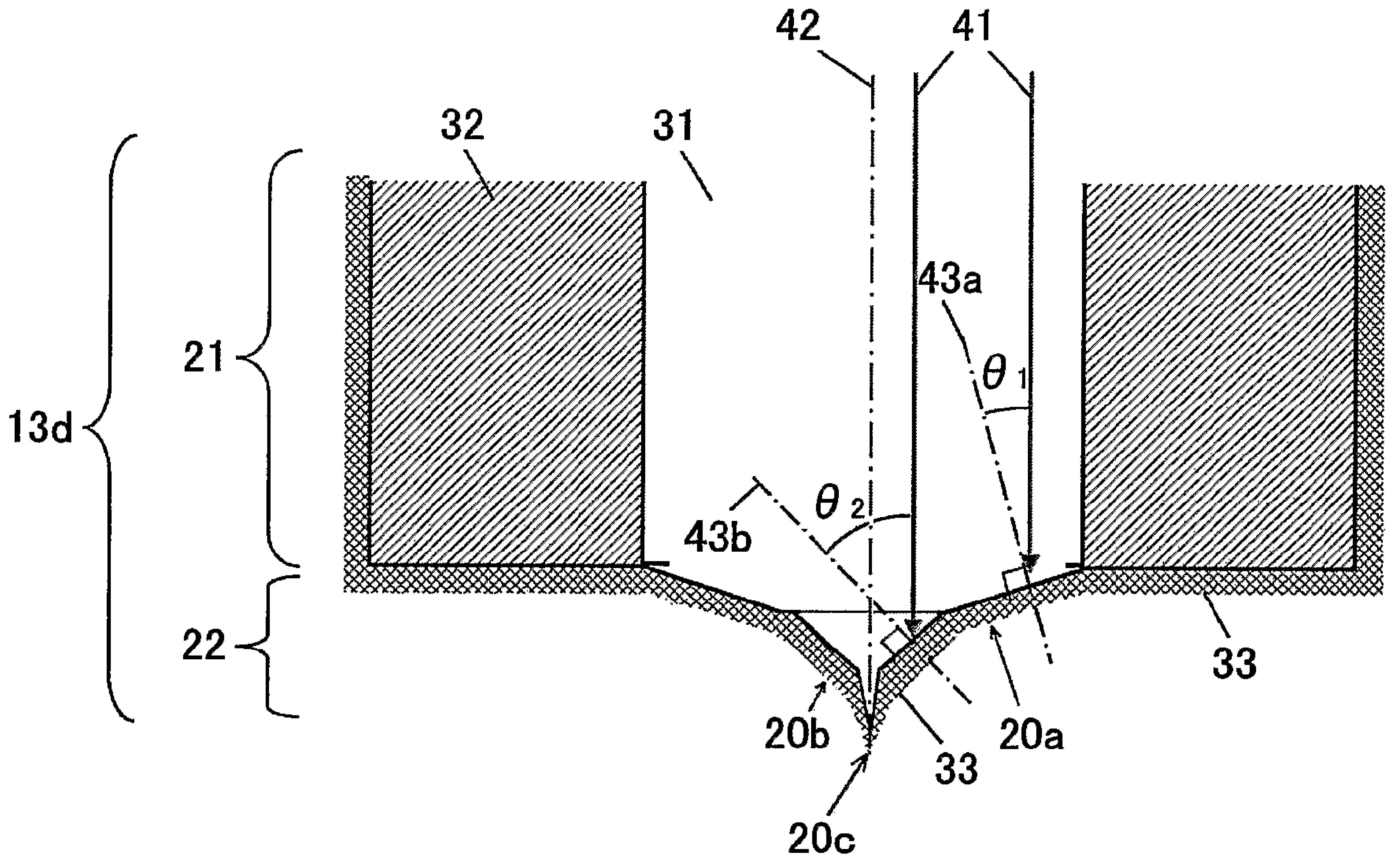


FIG.12



OPTICAL FIBER PROBE, OPTICAL DETECTION DEVICE, AND OPTICAL DETECTION METHOD

TECHNICAL FIELD

The present invention relates to an optical fiber probe used in a scanning probe microscope for measurements and manufacturing on a scale of nanometer, and an optical detection device, and an optical detection method.

BACKGROUND ART

With latest STM (Scanning Tunneling Microscope), AFM (Atomic Force Microscope), and other SPM (Scanning Probe Microscope) techniques, one is able to make measurements and manufacturing even on a nanometer scale. Among SPMs, a near-field microscope which is able to detect optical characteristics in a tiny area below a diffraction limit is used in measurements and evaluations in biotechnology and other fields. Additionally, research and development are being made of optical recording devices and fine-manufacturing device employing the above technique of the near-field microscope.

In the near-field microscope, a fine structure of a size below the diffraction limit is used as a probe, and a front end of the probe is illuminated to generate near-field light in proximity of the front end of the probe. If the probe is driven to scan the surface of a sample under this condition, the near-field light is scattered due to the electric-magnetic interaction between the near-field light localized in proximity of the probe and the surface of the sample, or the near-field light transmits through the sample. By detecting the scatted near-field light or the near-field light transmitting through the sample, it is possible to obtain optical information of the sample surface, such as light intensity, spectrum, and polarization.

In the near-field microscope, usually, the optical probe includes an optical fiber having a core and a clad layer around the core; the core has a sharpened end which is projecting out from an end of the fiber, thus forming a projecting portion of the optical probe, and, for example, the projecting portion is covered by Au, Ag, or other metals. With such an optical probe, it is possible to obtain an optical image having resolution higher than the light wavelength.

When measuring material properties in a small area of the sample by using the above near-field optical microscope, the shape of the sample can be measured by detecting evanescent light localized in a tiny area of the sample smaller than the light wavelength. Then, the evanescent light, which is generated when the sample is illuminated by light under conditions of total reflection, is scattered by the above optical probe, thus, being converted into scattered light. The scattered light is guided into the core of the optical fiber through the projection portion, and is detected by a detector connected to the other end (emission end) of the optical fiber. Namely, the near-field optical microscope scatters the light and detects the scatted light with the optical probe.

In the related art, although the near-field optical microscope is capable of measurements at high resolution, it suffers from a problem in that the coverage of measurements is small, specifically, it is only a few tens micron meters.

Recently, in applications, such as, detect inspections of silicon wafers, it is required that a measurement at high resolution be made by using the near-field light after a measurement in a wide range using ordinarily propagating light is finished so as to measure and inspect the same sample successively. To meet this requirement, a detect inspection device is proposed, for example, in Japanese Laid Open Patent Application No. 2000-55818, in which an optical probe for detection of near-field light is provided in a common optical microscope having an object lens-based observation system.

In the detect inspection device, when measuring certain material properties in a specified tiny area of a wide region covered by the object lens, it is necessary to align the position of the optical probe for the near-field light detection with respect to the tiny area, and then the near-field light detection (high resolution measurement) is made. However, it is very difficult to make the alignment of the optical probe to the tiny area, and the measurement is quite time consuming.

DISCLOSURE OF THE INVENTION

It is a general object of the present invention to solve one or more of the problems of the related art.

A specific object of the present invention is to provide an optical fiber probe, an optical detection device, and an optical detection method allowing quick measurements using near-field light at high resolution and high efficiency but without necessity of position alignment of the optical fiber probe.

According to an embodiment of the present invention, there is provided an optical fiber probe, comprising: a core for propagating light from a light source, a front end surface of said core including a first exit section for emitting the propagating light and a second exit section for seeping out near-field light, said first exit section and said second exit section being formed in a concentric manner, wherein the first exit section is formed on a peripheral side, and a tilt angle of a normal of the first exit section relative to an optical axis of the propagating light is different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light.

According to the present invention, it is possible to perform both a measurement in a wide range using the ordinarily propagating light and a measurement at high resolution using the near-field light with only one probe, and obtain a high Signal-to-Noise ratio in the high resolution measurement using the near-field light comparable to that in the wide range measurement using the ordinary light.

In addition, it is possible to efficiently collect light from the sample in the wide range measurement using the ordinary light, thus to reduce the measurement time.

These and other objects, features, and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments given with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is schematic view of an optical detection device **1** used in a near-field optical microscope according to an embodiment of the present invention;

FIG. **2** is an enlarged schematic view of an example of the optical probe **13** in the optical detection device **1**, in which the first taper portion has a conic shape;

FIG. **3** is an enlarged schematic view of an optical probe **13***a*, in which the first taper portion is curved;

FIG. **4** is a graph exemplifying a relationship between the distance from the front end of the optical probe **13** to the focused light spot and the tilt angle θ1 of the first taper portion **20***a* of the optical probe **13**;

FIG. **5** is a graph exemplifying a relationship between the distance from the front end of the optical probe to the focused light spot and a diameter ratio (B/A) of the second taper portion **22***b* and the first taper portion **22***a* of the optical probe **13**;

FIG. **6** is a graph exemplifying a relationship between the diameter of the light spot and the wavelength of the propagating light beam when the tilt angle θ1 of the first taper portion **22***a* of the optical probe **13** is 10°;

FIG. **7** is an enlarged schematic view of an optical probe **13***b*, in which the light-shielding layer **33** is provided only on the second taper portion **22***b;*

FIG. **8** is a graph showing a general light transmittance distribution, namely, a relationship between the light transmittance and the light wavelength;

FIG. **9** is a graph showing a relationship between the near-field light intensity and the light wavelength when the light-shielding layer **33** is an Au film;

FIG. **10** is a graph showing a relationship between the near-field light intensity and the tilt angle θ2 of the second taper portion **22***b;*

FIG. **11** is an enlarged schematic view of an example of an optical probe **13***c*, in which a front end portion of the second taper portion **22***b* is not covered by the light-shielding layer **33**; and

FIG. **12** is an enlarged schematic view of an example of an optical probe **13***d* in the optical detection device **1**, which further includes a third taper portion **30***c*.

BEST MODE FOR CARRYING OUT THE INVENTION

Below, preferred embodiments of the present invention are explained with reference to the accompanying drawings.

In the present invention, in addition to an optical probe structure taking into consideration a structure is devised to improve the characteristics of the light spot of the near-field light, thereby, in high resolution measurements using the near-field light, resolution and light utilization can be further improved. Specifically, in the optical probe structure of the present invention, on the front end surface of the core of the optical probe, a first exit section for emitting the propagating light and a second exit section for seeping out near-field light are arranged in a concentric manner with the first exit section being on the peripheral side, and the tilt angles of the normal of the first exit section and the normal of the second exit section relative to the optical axis of the propagating light are different from each other.

First, a description is made of a basic configuration of an optical detection device and a measurement process using the optical detection device with respect to FIG. **1**.

FIG. **1** is schematic view of an optical detection device **1** used in a near-field optical microscope according to an embodiment of the present invention.

For example, the optical detection device **1** shown in FIG. **1** can be used in a near-field optical microscope for measuring material properties in a small area of a sample.

As shown in FIG. **1**, the optical detection device **1** includes a light source **11**, a polarized beam splitter **12** arranged in the light path of the light from the light source **11**, a ¼ wave plate **18** arranged in the light path of the light passing through the polarized beam splitter **12**, an optical probe **13** for condensing the light passing through the ¼ wave plate **18** and illuminating on a surface **2***a* of a sample **2**, and an optical detector **14** for detecting light returned from the sample surface **2***a*.

The light source **11** is driven by a not-illustrated power supplier to oscillate. A wavelength conversion unit **17** is connected to the light source **11** and is able to change the wavelength of the light emitted from the light source **11**. The wavelength conversion unit **17** is used to control the diameter of the light spot of the light from the light source **11** by change the wavelength of the light.

The polarized beam splitter **12** allows the light from the light source **11** to pass through and directs the light to the sample surface **2***a*. At the same time, the polarized beam splitter **12** also reflects the light from the sample surface **2***a* and directs the light to the optical detector **14**.

The light transmitting through the polarized beam splitter **12** enters into the ¼ wave plate **18**.

The light from the light source **11** is linearly polarized. This linearly polarized light transmits through the ¼ wave plate **18** and is converted into circularly polarized light, and is incident into a core **31** of the optical probe **13**.

The returning light reflected on the sample surface **2***a*, which is circularly polarized, passes through the ¼ wave plate **18** again and is converted into linearly polarized light but in a polarization direction different from that of the light from the light source **11**, and this linearly polarized light is reflected by the polarized beam splitter **12**.

It should be noted that a common beam splitter could be used instead of the polarized beam splitter **12**.

The optical probe **13** includes a light guide portion **21** and a projecting portion **22** covered by a light-shielding layer **33**. The light guide portion **21** is formed by an optical fiber including a core **31** and a clad layer **32** around the core **31**. For example, the core **31** and the clad layer **32** are formed from silicon dioxide-based glass, and by adding germanium or phosphorous thereinto, the refractive index of the clad layer **32** is lower than that of the core **31**.

The projecting portion **22** is formed a conic portion of the core **31** projecting out from the clad layer **32** at an end of the light guide portion **21**. The projecting portion **22** includes a first taper portion **20***a* for emitting ordinarily propagating light and a second taper portion **20***b* for seeping out near-field light (Refer to FIG. **2**).

The optical probe **13** includes a probe controller **15**, corresponding to the "movement control unit" in claims of the present invention. For example, the probe controller **15** includes a three-axis actuator for moving the optical probe **13** to approach or depart from the sample surface **2***a*, or for driving the optical probe **13** to scan the sample surface **2***a* in a horizontal direction. Instead of moving the optical probe **13** to approach or depart from the sample surface **2***a*, the probe controller **15** may move the sample surface **2***a* to approach or depart from the optical probe **13**.

The optical detector **14** receives the returning light from the sample surface **2***a*, and converts the light into electric signals to generate a brightness signal. An image is formed based on the brightness signal and is displayed on a not-illustrated display. A user can measure and observe details of the sample surface **2***a* by using the displayed image.

As for the method of detecting the returning light form the sample surface **2***a*, when the sample **2** is light transmissive, the optical detector **14** may be located opposite to the optical probe **13** with the sample **2** in between.

FIG. **2** is an enlarged schematic view of an example of the optical probe **13** in the optical detection device **1**, in which a first taper portion **22***a* has a conic shape.

First, a description is made of a structure of the first taper portion **20***a* for emitting the ordinary propagating light and characteristics of the light spot of the ordinary propagating light.

In FIG. **2**, the ordinary propagating light **41**, which propagates in the core **31**, arrives at the first taper portion **20***a*, and is emitted out of the optical probe **13** from the first taper portion **20***a*.

Here, the surface **22***a* of the first taper portion **20***a* of the optical probe **13** is of a conic taper shape, and the normal **43***a* of the surface **22***a* and the optical axis **42** of the propagating light subtends an angle θ**1**. Below, the angle θ**1** is referred to as a tilt angle θ**1**.

Preferably, the tilt angle θ1 is less than the total reflection angle of the propagating light **41** and is greater than zero degree.

With such a configuration, after transmitting through the light-shielding layer **33**, a large portion of the light propagating in the optical probe **13** is refracted and is emitted out of the optical probe **13**, and is focused at a position apart from the front end of the optical probe **13** by a few hundreds nm through a few μm, forming a light spot of high intensity.

The first taper portion **20***a* of the optical probe **13** may have other shapes, instead of the conic taper shape as shown in FIG. **2**.

FIG. **3** is an enlarged schematic view of an optical probe **13***a*, in which the first taper portion is curved.

The reason why the light is focused at a position to form light spot of high intensity apart from the front end of the optical probe **13** is because the tilt angle θ1 is less than the total reflection angle of the propagating light **41**. In the optical probe of the related art, the tilt angle θ**1** is greater than the total reflection angle of the propagating light **41**, the light intensity is at a maximum near the front end of the optical probe **13** and drops rapidly at positions far from the front end of the optical probe **13**, thus, the light spot is of low light intensity.

The distance between the focused light spot and the front end of the optical probe **13** can be controlled by adjusting the tilt angle θ**1** of the first taper portion **20***a*.

FIG. **4** is a graph exemplifying a relationship between the distance from the front end of the optical probe **13** to the focused light spot and the tilt angle θ**1** of the first taper portion **20***a* of the optical probe **13**.

When the refractive index of the first taper portion **20***a* is 1.53, and the medium into which the light is emitted is air, the total reflection angle is 40°. As shown in FIG. **4**, when the incidence angle (tilt angle) is less than 40°, the propagating light is focused, thus forming a light spot at a position apart from the front end of the optical probe **13** by a few hundreds nm through a few μm.

In addition, in order to form a light spot at a position apart from the front end of the optical probe **13**, it is required that the ratio of the diameter B of the second taper portion **22***b* ratio and the diameter A of the first taper portion **22***a* (refer to FIG. **2**) of the optical probe **13** be relatively small.

FIG. **5** is a graph exemplifying a relationship between the distance from the front end of the optical probe to the focused light spot and a diameter ratio (B/A) of the second taper portion **22***b* and the first taper portion **22***a* of the optical probe **13**.

As shown in FIG. **5**, when the diameter ratio (B/A) is less than 0.25, the propagating light is focused, thus forming a light spot at a position apart from the front end of the optical probe **13**.

The diameter of the light spot can be controlled by adjusting the diameter D of the foot of the first taper portion **22***a*, the tilt angle θ**1** of the first taper portion **20***a*, and the wavelength of the propagating light **41**. For example, the diameter D of the foot of the first taper portion **22***a*, the tilt angle θ**1** of the first taper portion **20***a*, and the wavelength of the propagating light can be adjusted so that the diameter of the light spot is comparable to required measurement resolution. Specifically, the diameter of the light spot can be reduced by reducing the diameter D of the foot of the first taper portion **22***a*, increasing the tilt angle θ**1** of the first taper portion **20***a*, and reducing the wavelength of the propagating light **41**.

FIG. **6** is a graph exemplifying a relationship between the diameter of the light spot and the wavelength of the propagating light beam when the tilt angle θ**1** of the first taper portion **22***a* of the optical probe **13** is 10°.

In the example shown in FIG. **6**, light is emitted from the first taper portion **22***a* having a refractive index of 1.53 to the air. If the light spot diameter can be adjusted to be 0.4 μm (FWHM (Full Width at Half Maximum)) by setting the diameter D of the foot of the first taper portion **22***a* to 2 μm, the tilt angle θ**1** of the first taper portion **20***a* to 20°, and the wavelength of the propagating light **41** to 0.4 μm. In this case, the distance from the front end of the optical probe to the focused light spot is 1.2 μm.

The light-shielding layer **33** arranged on the optical probe **13** is used for forming the light spot of the near-field light in measurements using the near-field light (high resolution measurements). The light-shielding layer **33** may be arranged on the optical probe **13** in various ways.

FIG. **7** is an enlarged schematic view of an optical probe **13***b*, in which the light-shielding layer **33** is provided only on the second taper portion **22***b*.

Generally, the optical probe **13** shown in FIG. **2** has relatively low intensity of the emitting light compared to the optical probe **13***b* shown in FIG. **7**, but by adjusting the material and thickness of the light-shielding layer **33**, and selecting the wavelength of the light from the light source **11**, measurements can be made with the propagating light by using the optical probe **13**.

For example, when the material of the light-shielding layer **33** is Au, and the thickness thereof is 80 nm, it has been confirmed that the light is focused at a position apart from the front end of the optical probe **13** by a few hundreds nm through a few μm, and a light spot of high intensity is formed.

Further, considering the dispersion characteristics associated with the birefringence property of the light-shielding layer **33**, it is preferable to select the wavelength of the light from the light source **11** to be equal to or near a value resulting in a maximum light transmittance of the light-shielding layer **33**. In doing so, it is possible to improve intensity of the light emitted from the optical probe **13**.

FIG. **8** is a graph showing a general light transmittance distribution, namely, a relationship between the light transmittance and the light wavelength.

In FIG. **8**, assume the maximum light transmittance is T**0**, and half of the maximum light transmittance is T**1**; the wavelengths corresponding to the light transmittance T**1** are λ_{11} and λ_{12}. Here, the wavelength approximately resulting in the maximum light transmittance TO includes the wavelengths from the wavelength λ_{11} to the wavelength λ_{12} (the hatched region in FIG. **8**). For example, when the material of the light-shielding layer **33** is Au, λ_{11} is 480 nm and λ_{12} is 700 nm.

Next, the structure of the second taper portion **20***b* of the optical probe **13** for seeping out the near-field light is described, again, with reference to FIG. **2**.

As shown in FIG. **2**, among the light **41** propagating in the core **31**, a light component near the optical axis of the optical fiber arrives at the second taper portion **20***b*, and is incident to the second taper portion **20***b*.

Here, the surface **22***b* of the second taper portion **20***b* of the optical probe **13** has a conic taper shape, and the normal **43***b* of the surface **22***b* and the optical axis **42** of the propagating light subtends an angle θ**2**. Below, the angle θ**2** is referred to as a tilt angle θ**2**.

Preferably, the tilt angle θ2 is greater than or equal to the total reflection angle of the propagating light **41** and is less than 90°.

In such a configuration, a large portion of the light propagating in the optical probe **13** is reflected on the interface between the light-shielding layer **33** and the core **31** of the optical probe **13**, but a small portion of the light **41** transmits through the light-shielding layer **33** (this is described as "seep" here), and propagates along the light-shielding layer **33** to the front end of the optical probe **13**, becoming local surface plasmon at the front end. Due to the surface plasmon obtained as described above, a light spot can be formed near the front end of the optical probe **13**, this is referred to as near-field light spot.

The light-shielding layer **33** may be any material. In order to strengthen the near-field light generated by the surface plasmon, it is preferable to use an Au film. The Au film is also superior in chemical stability.

FIG. **9** is a graph showing a relationship between the near-field light intensity and the light wavelength when the light-shielding layer **33** is an Au film.

By selecting the wavelength of the incident light based on the dependence of the near-field light intensity on the light wavelength, it is possible to increase the intensity of the near-field light seeping out from the optical probe **13**. For example, the wavelength approximately resulting in the maximum near-field light intensity **P0** can be selected.

Generally, the distribution of the near-field light intensity exhibits a peak as shown in FIG. **9**. Assume the maximum intensity of the near-field light is **P0**, and half of the maximum intensity is **P1**; the wavelengths corresponding to the light intensity **P1** are λ_{11} and λ_{12}.

Here, the wavelength approximately resulting in the maximum near-field light intensity **P0** includes the wavelengths from the wavelength λ_{11} to the wavelength λ_{12} (the hatched region in FIG. **9**), and wavelengths from λ_{11} to λ_{12} can be selected.

For example, when the light-shielding layer **33** is an Au film, λ_{11} is about 480 nm and λ_{12} is about 700 nm.

FIG. **10** is a graph showing a relationship between the near-field light intensity and the tilt angle θ2 of the second taper portion **22***b*.

Similar to the descriptions of the dependence of the near-field light intensity on the light wavelength, the near-field light intensity also depends on the tilt angle θ2 of the second taper portion **22***b*. By selecting the wavelength of the incident light based on the dependence of the near-field light intensity on the tilt angle θ2 of the second taper portion **22***b*, it is possible to increase the intensity of the near-field light seeping out from the optical probe **13**. For example, the tilt angle θ2 approximately resulting in the maximum near-field light intensity **P0** can be selected.

Generally, the dependence of the near-field light intensity on the tilt angle θ2 exhibits a peak as shown in FIG. **10**. Assume the maximum intensity of the near-field light is **P0**, and half of the maximum intensity **P0** is **P1**; the tilt angles θ2 corresponding to the light intensity **P1** are θ_a and θ_b.

For example, Here, the tilt angle θ2 approximately resulting in the maximum near-field light intensity **P0** is from the tilt angle θ_a to the tilt angle θ_b (the hatched region in FIG. **10**), and the tilt angle from θ_a to θ_b can be selected.

For example, when the light-shielding layer **33** is an Au film, and the wavelength of the incident light is 532 nm, θ_a is about 45° and θ_b is about 55°.

The light-shielding layer **33** may be arranged on the optical probe **13** in further different ways from those in the optical probe **13**, optical probe **13***a*, and optical probe **13***b* shown in FIG. **2**, FIG. **3**, and FIG. **7**.

FIG. **11** is an enlarged schematic view of an example of an optical probe **13***c*, in which a front end portion of the second taper portion **22***b* is not covered by the light-shielding layer **33**.

In FIG. **11**, the second taper portion **22***b*, which is for seeping out near-field light, is not completely covered by the light-shielding layer **33**, but the light-shielding layer **33** is not provided at the front end of the second taper portion **22***b*, leaving a small opening. With such a configuration, it is possible to form a high intensity light spot of the near-field light, enabling measurements of a high Signal-to-Noise Ratio (SNR).

FIG. **12** is an enlarged schematic view of an example of an optical probe **13***d* in the optical detection device **1**, which further includes a third taper portion **30***c*.

In the measurements using the near-field light (high resolution measurements), the measurement resolution is approximately determined by the curvature radius of the front end of the optical probe **13**, and high measurement resolution is obtainable when the curvature radius of the front end is small.

Generally, in order to reduce the curvature radius of the front end of the optical probe **13**, it is required that the optical probe **13** is highly sharpened. However, as described above, when the shape of the second taper portion **22***b* is adjusted to produce the maximum intensity of the near-field light, it becomes difficult to make the optical probe **13** sharp, and thus, with the optical probe **13** shown in FIG. **2**, it is difficult to obtain both high intensity near-field light and high measurement resolution.

The optical probe **13***d* can be used to solve this problem, which further includes the third taper portion **30***c*, in addition to the components of the optical probe **13** in FIG. **2**.

In FIG. **12**, the tilt angle (not illustrated) of the third taper portion **30***c* is greater than the tilt angle θ_2 of the second taper portion **22***b* and less than 90°. Preferably, the tilt angle of the third taper portion **30***c* is large, because the optical probe **13** becomes sharper.

Next, a measurement process with the optical detection device **1** having the above structure as shown in FIG. **1** is described.

First, a wide range measurement using the ordinary propagating light is described.

The light from the light source **11** including a linearly polarized light component transmits through the polarized beam splitter **12**, the polarization state thereof is modified by the ¼ wave plate **18**, then, the light is incident into the core **31** of the optical probe **13**. The incident light propagates in the core **31**, is emitted out from the optical probe **13**, and is focused, and thus forms a light spot, at a position apart from the front end of the optical probe **13**.

Then, the probe controller **15** moves the optical probe **13** to approach or depart from the sample surface **2***a* so as to locate the sample surface **2***a* at the position of the light spot. In this process of positioning the optical probe **13**, it is necessary to information of the distance between the focused light spot and the front end of the optical probe **13**, and this information can be measured experimentally in advance.

Next, the probe controller **15** drives the optical probe **13** to scan the sample surface **2***a* in the horizontal direction. In this step, the light emitted from the optical probe **13** is returned from the sample surface **2***a*, and the optical detector **14** receives the returning light, and generates a brightness signal, and based on the brightness signal, an image is formed and is displayed on a not-illustrated display. From the image, detailed material property information of the sample surface **2***a* is obtainable.

When the optical probe **13** scans the sample surface **2***a* in the horizontal direction, the optical probe **13** may be set at a specific height relative to the sample surface **2***a*. In doing so, it is not necessary to perform control in the direction of approaching and departing, and together with the information of the distance between the focused light spot and the front end of the optical probe **13** (a few hundreds nm to a few μm), it is possible to perform scanning at high speed, and thus reducing the measurement time greatly. Compared to near-field light measurements of the related art, since the measurement range per one point is large in the present invention, measurements in a wider range can be realized with the same number of measurement points or measurement lines.

Further, compared to the case in which the light emitted out from the optical probe **13** is not focused, in the present invention, it is possible to collect a relatively large amount of the returning light from the sample surface **2***a*, as a result, it is possible to obtain measurement results of high contrast due to an improved Signal-to-Noise ratio in measurements using the ordinary light.

Therefore, it is possible to provide an optical detection device capable of efficient light detection at high speed in the wide range measurement using the ordinary propagating light.

Next, a high resolution measurement using the near-field light is described.

The light from the light source **11** including a linearly polarized light component transmits through the polarized beam splitter **12**, the polarization state thereof is modified by the ¼ wave plate **18**, then, the light is incident into the core **31** of the optical probe **13**. The incident light propagates in the core **31**, and enters into the light-shielding layer **33** of the optical probe **13**. In this step, at the exit end of the light-shielding layer **33**, near-field light, which is evanescent light, seeps out. With the near-field light seeping out, the probe controller **15** moves the optical probe **13** to approach the sample surface **2***a*. At this moment, when the distance between the front end of the optical probe **13** and the sample surface **2***a* less than a quarter of the wavelength of the light from the light source **11**, the near-field light seeping out from the optical probe **13** illuminates the sample surface **2***a*, and a tiny light spot of the near-field light is formed on the sample surface **2***a*. The near-field light forming the tiny light spot transmits through the light-shielding layer **33** and is directed to the optical detector **14** via the core **31**. In this way, it is possible to perform a high resolution measurement on the sample surface **2***a*.

As described above, by moving the one optical probe **13** to approach or depart from the sample surface **2***a*, it is possible to selectively change the light spot of the near-field light and the light spot of the propagating light on the sample surface **2***a*, it is possible to perform both a wide range measurement using the propagating light and a high resolution measurement using the near-field light with only one optical probe.

In addition, in such a measurement system able to a high resolution measurement using the near-field light, it is not necessary to install a separate optical probe for the wide range measurement, thus the size of the system and the number of parts are reduced, and this reduces the cost of the system.

Next, a description is made of a process of performing a measurement at high resolution by using the near-field light after a measurement in a wide range by using the propagating light is finished so as to measure and inspect the same sample successively.

The light from the light source **11** including a linearly polarized light component transmits through the polarized beam splitter **12**, the polarization state thereof is modified by the ¼ wave plate **18**, then, the light is incident into the core **31** of the optical probe **13**. The incident light propagates in the core **31**, is emitted out from the optical probe **13**, and is focused, and thus forms a light spot, at a position apart from the front end of the optical probe **13**.

Then, the probe controller **15** moves the optical probe **13** to approach or depart from the sample surface **2***a* so as to locate the sample surface **2***a* at the position of the light spot. Information of the distance between the focused light spot and the front end of the optical probe **13**, which is used in this process of positioning the optical probe **13**, can be measured experimentally in advance.

Next, the probe controller **15** drives the optical probe **13** to scan the sample surface **2***a* in the horizontal direction. In this step, the light emitted from the optical probe **13** is returned from the sample surface **2***a*, and the optical detector **14** receives the returning light, and generates a brightness signal, and based on the brightness signal, an image is formed and is displayed on a not-illustrated display. From the image, detailed material property information of the sample surface **2***a* is obtainable.

From the optical material property information of the sample surface **2***a* obtained from the displayed image, the user specifies a tiny region in which more detailed measurements of the material property are desired. The optical probe **13** is moved in the horizontal direction to align the position of the optical probe **13** to the tiny region, and then the high resolution measurement using the near-field light, as described above, is performed.

In this way, the high resolution measurement using the near-field light is performed after the wide range measurement using the propagating light is finished to measure and inspect the same sample successively, it is not necessary to exchange the optical probe to be used, and the high resolution measurement can be performed with the same axis as the wide range measurement. Hence, it is possible to reduce workload of the user, and the high resolution measurement can be performed with the optical probe which has been already positioned precisely at the desired tiny region.

According to the present invention, the light propagating from the optical fiber to the optical probe is incident at an incidence angle less than the total reflection angle and is greater than zero, and is emitted out from the first exit section as ordinary light. Additionally, the light propagating from the optical fiber to the optical probe is incident at an incidence angle different from the incidence angle relative to the first exit section, and is seeped out from the second exit section. Because the intensity of the light emitted out from the optical probe is increased, a light spot of the ordinary light is formed at a position apart from the front end of the optical probe, and a light spot of the near-field light is formed at a position near the front end of the optical probe.

In addition, because the tilt angle of the normal of the second exit section relative to the optical axis of the propagating light is set to be greater than or equal to a total reflection angle of the propagating light and is less than 90 degrees, it is possible to form the light spot of strong near-field light near the front end of the optical probe.

In addition, because the second exit section includes the first portion and the second portion on the inner side of the first portion, the tilt angle of the normal of the second portion of the second exit section is greater than the tilt angle of the normal of the first portion and is less than 90 degrees, it is possible to reduce the curvature radius of the front end of the optical probe, hence, it is possible to generate strong near-field light near the front end of the optical probe, and improve the resolution in measurements using the near-field light.

Further, because the light spot of the ordinary light is formed apart from the front end of the optical probe, and the light spot of the near-field light is formed near the front end of the optical probe, it is possible to perform both a measurement in a wide range using the ordinary light and a measurement at high resolution using the near-field light with only one probe.

Because a wavelength control unit is provided to control the light wavelength based on the material and thickness of the light-shielding layer, the tilt angle of the normal of the first exit section, and the tilt angle of the normal of the second exit section, it is possible to obtain a desired light spot diameter, light intensity, and focus position in measurements using the ordinary light, further, it is possible to obtain high intensity of the near-field light in measurements using the near-field light.

In addition, it is possible to obtain detection signals of a high Signal-to-Noise ratio in measurements using the near-field light.

Further, it is possible to obtain a light spot of high intensity, and obtain measurement results of high contrast due to an improved Signal-to-Noise ratio in measurements using the ordinary light.

Because the tilt angle of the normal of the second exit section is adjusted so that intensity of the near-field light on the surface of the light-shielding layer in the second exit section is equal to or near a maximum while considering the material of the light-shielding layer and the wavelength of the incident light, it is possible to generate strong near-field light.

By further controlling the wavelength control unit using the wavelength control unit, it is possible to generate strong near-field light.

Further, it is possible to obtain a desired light spot diameter and a desired focus position.

It is possible to obtain both strong near-field light and high resolution, and to select appropriate measurement resolution.

Because the light from the sample can be collected efficiently in the wide range measurement using the ordinary light, it is possible to reduce the measurement time.

While the present invention is above described with reference to specific embodiments chosen for purpose of illustration, it should be apparent that the invention is not limited to these embodiments, but numerous modifications could be made thereto by those skilled in the art without departing from the basic concept and scope of the invention.

This patent application is based on Japanese Priotity Patent Application No. 2005-029652 filed on Feb. 4, 2005, the entire contents of which are hereby incorporated by reference.

The invention claimed is:

1. An optical fiber probe, comprising:

a core configured to propagate light from a light source, a front end surface of said core including a first exit section configured to emit the propagating light and a second exit section configured to seep out near-field light, said first exit section and said second exit section being disposed in a concentric manner,

wherein

a tilt angle of a normal of the first exit section relative to an optical axis of the propagating light is different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light,

the first exit section extends from a peripheral side of the optical fiber probe and projects immediately outward, at least partially in a direction parallel to the optical axis, from an edge of a clad layer at an end of a light guide portion in the core, and

the tilt angle of the normal of the second exit section is about 45 to 55 degrees.

2. The optical fiber probe as claimed in claim **1**, wherein the tilt angle of the normal of the first exit section relative to the optical axis of the propagating light is less than a total reflection angle of the propagating light and is greater than zero.

3. The optical fiber probe as claimed in claim **1**, wherein the tilt angle of the normal of the second exit section relative to the optical axis of the propagating light is greater than or equal to a total reflection angle of the propagating light and is less than 90 degrees.

4. The optical fiber probe as claimed in claim **1**, wherein

the second exit section includes a first portion and a second portion on an inner side of the first portion,

a tilt angle of a normal of the first portion of the second exit section relative to the optical axis of the propagating light is greater than or equal to a total reflection angle of the propagating light and is less than 90 degrees, and

a tilt angle of a normal of the second portion of the second exit section relative to the optical axis of the propagating light is greater than the tilt angle of the normal of the first portion and is less than 90 degrees.

5. The optical fiber probe as claimed in claim **1**, wherein the first exit section is curved when viewed along an axis perpendicular to an axis of the core.

6. The optical fiber probe as claimed in claim **1**, wherein the tilt angle of the normal of the first exit section is shaped to control a distance between the front end surface of said core and a focused light spot of the propagating light disposed on a surface of a sample such that the distance between the front end surface of said core and the focused light spot is less than 2 μm.

7. An optical fiber probe, comprising:

a core configured to propagate light from a light source, a front end surface of said core being covered by a light-shielding layer configured to seep out near-field light, the front end surface of said core including a first exit section configured to emit the propagating light and a second exit section configured to seep out the near-field light, said first exit section and said second exit section being disposed in a concentric manner,

wherein

a tilt angle of a normal of the first exit section relative to an optical axis of the propagating light is different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light,

the first exit section extends from a peripheral side of the optical fiber probe and projects immediately outward, at least partially in a direction parallel to the optical axis, from an edge of a clad layer at an end of a light guide portion in the core, and

the tilt angle of the normal of the second exit section is about 45 to 55 degrees.

8. An optical detection device, comprising:

a light source;

an optical fiber probe including a core configured to propagate light from the light source, an optical probe being disposed at a front end of said core;

a movement control unit configured to move the optical fiber probe and a surface of a sample to approach or depart from each other so that a light spot of the propagating light or near-field light seeping out from the front end of the core is disposed on the surface of the sample; and

a detection unit configured to detect light from the surface of the sample,

wherein

the optical probe includes a first exit section on the front end surface of the core configured to emit the propagating light and a second exit section on the front end surface of the core configured to seep out the near-field light,

the first exit section and the second exit section are disposed in a concentric manner,

a tilt angle of a normal of the first exit section relative to an optical axis of the propagating light is different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light,

the first exit section extends from a peripheral side of the optical fiber probe and projects immediately outward, at least partially in a direction parallel to the optical axis, from an edge of a clad layer at an end of a light guide portion in the core, and

the tilt angle of the normal of the second exit section is about 45 to 55 degrees.

9. The optical detection device as claimed in claim **8**, wherein the tilt angle of the normal of the first exit section relative to the optical axis of the propagating light is less than a total reflection angle of the propagating light and is greater than zero.

10. The optical detection device as claimed in claim **8**, wherein the tilt angle of the normal of the second exit section relative to the optical axis of the propagating light is greater than or equal to a total reflection angle of the propagating light and is less than 90 degrees.

11. The optical detection device as claimed in claim **8**, wherein

the second exit section includes a first portion and a second portion on an inner side of the first portion,

a tilt angle of a normal of the first portion of the second exit section relative to the optical axis of the propagating light is greater than or equal to a total reflection angle of the propagating light and is less than 90 degrees, and

a tilt angle of a normal of the second portion of the second exit section relative to the optical axis of the propagating light is greater than the tilt angle of the normal of the first portion and is less than 90 degrees.

12. The optical detection device as claimed in claim **8**, wherein the tilt angle of the normal of the first exit section is adjusted so that a shape of the light spot becomes a predetermined shape.

13. The optical detection device as claimed in claim **8**, wherein a diameter of the optical probe is adjusted so that a shape of the light spot of the light propagating in the core becomes a predetermined shape.

14. The optical detection device as claimed in claim **8**, wherein the tilt angle of the normal of the first exit section and a diameter of the optical probe are adjusted so that a shape of the light spot of the light propagating in the core becomes a predetermined shape.

15. An optical detection device, comprising:

a light source;

an optical fiber probe including a core configured to propagate light from the light source, an optical probe being disposed at a front end of said core, the front end surface of said core being covered by a light-shielding layer configured to seep out near-field light;

a movement control unit configured to move the optical fiber probe and a surface of a sample to approach or depart from each other so that a light spot of the propagating light or near-field light seeping out from the front end of the core is disposed on the surface of the sample; and

a detection unit configured to detect light from the surface of the sample,

wherein

the optical probe includes a first exit section on the front end surface of the core configured to emit the propagating light and a second exit section on the front end surface of the core configured to seep out the near-field light,

the first exit section and the second exit section are disposed in a concentric manner,

a tilt angle of a normal of the first exit section relative to an optical axis of the propagating light is different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light,

the first exit section extends from a peripheral side of the optical fiber probe and projects immediately outward, at least partially in a direction parallel to the optical axis, from an edge of a clad layer at an end of a light guide portion in the core, and

the tilt angle of the normal of the second exit section is about 45 to 55 degrees.

16. The optical detection device as claimed in claim **15**, further comprising:

a wavelength control unit configured to control a wavelength of the light from the light source to be a predetermined wavelength based on a material and a thickness of the light-shielding layer, the tilt angle of the normal of the first exit section, and the tilt angle of the normal of the second exit section.

17. The optical detection device as claimed in claim **16**, wherein the predetermined wavelength is equal to or near a value resulting in a maximum intensity of the near-field light on a surface of the light-shielding layer.

18. The optical detection device as claimed in claim **16**, wherein the predetermined wavelength is equal to or near a value resulting in a maximum light transmittance of the light-shielding layer.

19. The optical detection device as claimed in claim **15**, wherein the tilt angle of the normal of the second exit section is adjusted so that intensity of the near-field light on a surface of the light-shielding layer in the second exit section is equal to or near a maximum.

20. The optical detection device as claimed in claim **15**, further comprising:

a wavelength control unit configured to control a wavelength of the light from the light source,

wherein

the wavelength control unit is controlled and the tilt angle of the normal of the second exit section is adjusted so that intensity of the near-field light on a surface of the light-shielding layer in the second exit section is equal to or near a maximum.

21. An optical detection method, comprising the steps of:

propagating light from a light source to a core of an optical fiber probe, said optical fiber probe including an optical probe being disposed at a front end of the core, the optical probe including a first exit section on the front end surface of the core configured to emit the propagating light and a second exit section on the front end surface configured to seep out the near-field light, the first exit section and the second exit section being disposed in a concentric manner, a tilt angle of a normal of the first exit section relative to an optical axis of the propagating light being different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light, the first exit section extending from a peripheral side of the optical fiber probe and projecting immediately outward, at least partially in a direction parallel to the optical axis, from an edge of a clad layer at an end of a light guide portion in the core, the tilt angle of the normal of the second exit section is about 45 to 55 degrees;

moving the optical fiber probe and the surface of the sample to approach or depart from each other so that the light spot of the propagating light or near-field light seeping out from the front end of the core is formed on the surface of the sample; and

detecting light from the surface of the sample.

22. An optical detection method, comprising the steps of:

propagating light from a light source to a core of an optical fiber probe, said optical fiber probe including an optical probe being disposed at a front end of the core, the optical probe including a first exit section on the front end surface of the core configured to emit the propagating light and a second exit section on the front end surface configured to seep out the near-field light, the first exit section and the second exit section being disposed in a concentric manner, a tilt angle of a normal of

the first exit section relative to an optical axis of the propagating light being different from a tilt angle of a normal of the second exit section relative to the optical axis of the propagating light, the first exit section extending from a peripheral side of the optical fiber probe and projecting immediately outward, at least partially in a direction parallel to the optical axis, from an edge of a clad layer at an end of a light guide portion in the core, the tilt angle of the normal of the second exit section is about 45 to 55 degrees, and at least the second exit section of the front end surface being covered by a light-shielding layer configured to seep out near-field light;

moving the optical fiber probe and the surface of the sample to approach or depart from each other so that the light spot of the propagating light or the near-field light seeping out from the front end of the core is formed on the surface of the sample; and

detecting light from the surface of the sample.

23. The method as claimed in claim **22**, further comprising a step of:

controlling a wavelength of the light from the light source to be a predetermined wavelength based on a material and a thickness of the light-shielding layer, the tilt angle of the normal of the first exit section, and the tilt angle of the normal of the second exit section.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 7,586,084 B2 Page 1 of 1
APPLICATION NO. : 11/547032
DATED : September 8, 2009
INVENTOR(S) : Izumi Itoh et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title Page, Item 86, change “PCT/JP2006/002205” to --PCT/JP2006/302205--.

Signed and Sealed this

Seventeenth Day of November, 2009

David J. Kappos

David J. Kappos
Director of the United States Patent and Trademark Office